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May, 2024

2024 Topical Collaboration Principal Investigators' Exchange Meeting

# ExoHad Status

Eric Swanson

EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

# Collaboration Overview

## goals of the collaboration

- Provide an unambiguous identification of the lowest-lying exotic hybrid, the isovector $\pi_1$ with $J^{PC} = 1^{-+}$;
- Obtain robust predictions for the hybrid-meson partners with differing quantum numbers;
- Develop robust techniques to study low-lying resonances, and provide metrics that may distinguish between conventional and unconventional hadrons;
- Set a foundation for future QCD spectroscopy efforts.

## Spokepersons

Raúl Briceño
University of California, Berkeley

Eric Swanson
University of Pittsburgh

## Full Members

Eric Braaten
Ohio State University

Raúl Briceño
University of California, Berkeley

Michael Döring
George Washington University

Jo Dudek
William & Mary

Robert Edwards
Jefferson Lab

Gernot Eichmann
Universität Graz

César Fernández Ramírez
National University of Distance Education

Christian Fischer
JLU Giessen

Andrew Jackura
William & Mary

Rich Lebed
Arizona State University

Jinfeng Liao
Indiana University

Vincent Mathieu
University of Barcelona

Emilie Passemar
Indiana University

Alessandro Pilloni
Università di Messina

Arkaitz Rodas Bilbao
Old Dominion University / Jefferson Lab

Stephen Sharpe
University of Washington

Eric Swanson
University of Pittsburgh

Adam Szczepaniak
Indiana University

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Indiana University

## Students and Postdocs


Roberto Bruschini
Ohio State University


Zack Draper
University of Washington


Yuchuan Feng
George Washington University


Md Habib E Islam
Old Dominion University


Joshua Hoffer
JLU Giessen


Markus Huber
JLU Giessen


Kevin Ingles
Ohio State University


Sebastian Marek Dawid
University of Washington


Gloria Montaña
Jefferson Lab

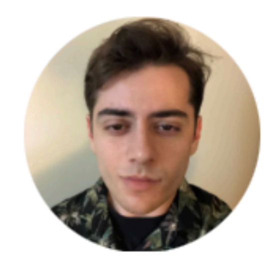

Franziska Münster
JLU Giessen


Felipe Ortega Gama
William & Mary


Robert Perry
University of Barcelona


Justin Pickett
Ohio State University


Vanamali Shastry
Indiana University


Wyatt Smith
George Washington University

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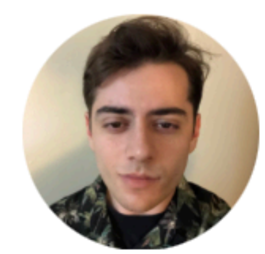
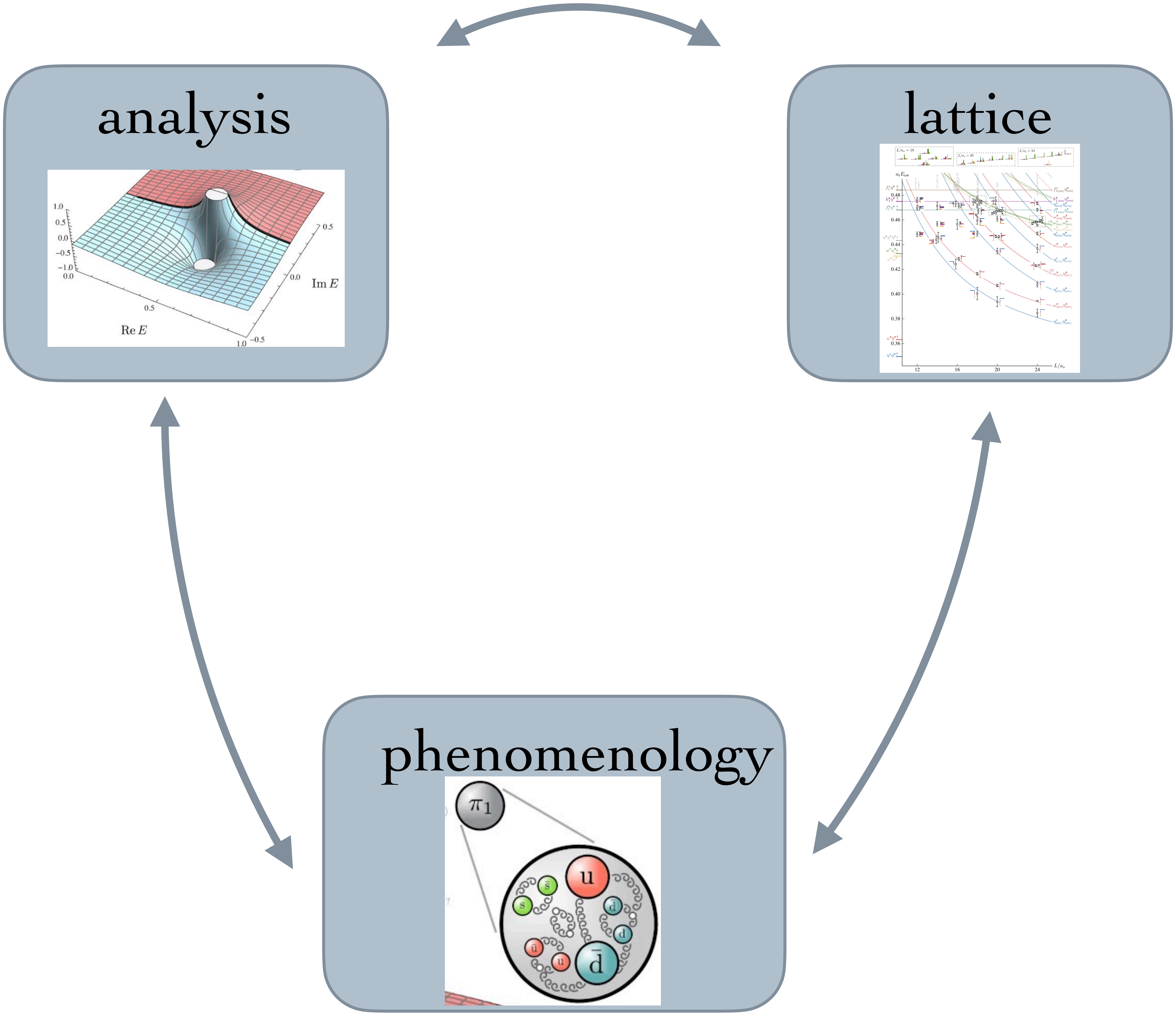
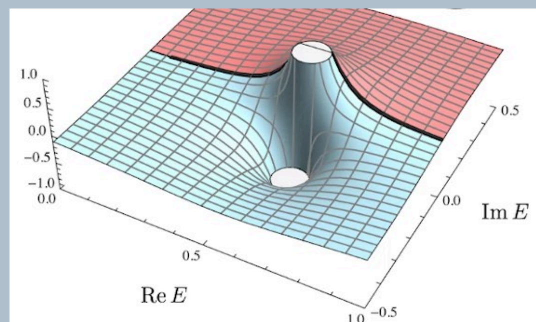
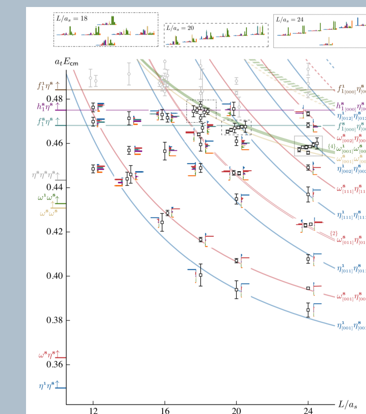

Wyatt Smith
George Washington University


analysis
lattice
phenomenology
Re $E$
Im $E$
$\pi_1$

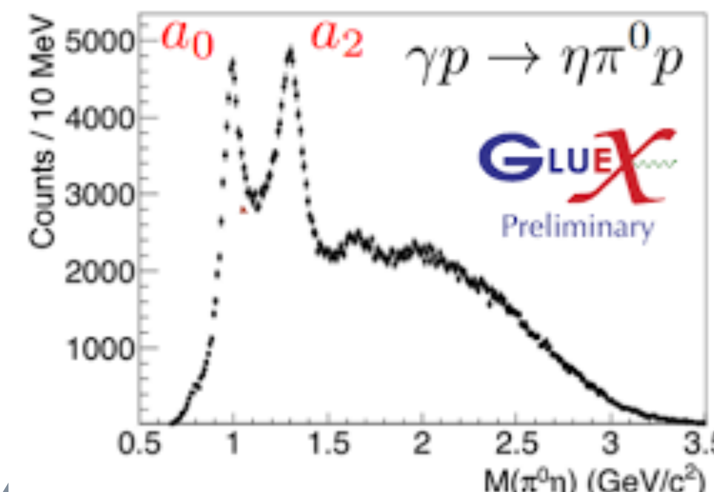
analysis



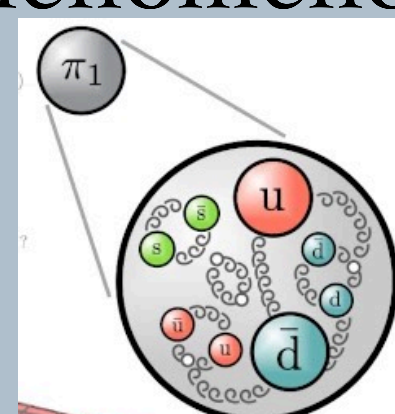

lattice



discovery of hybrid mesons




phenomenology



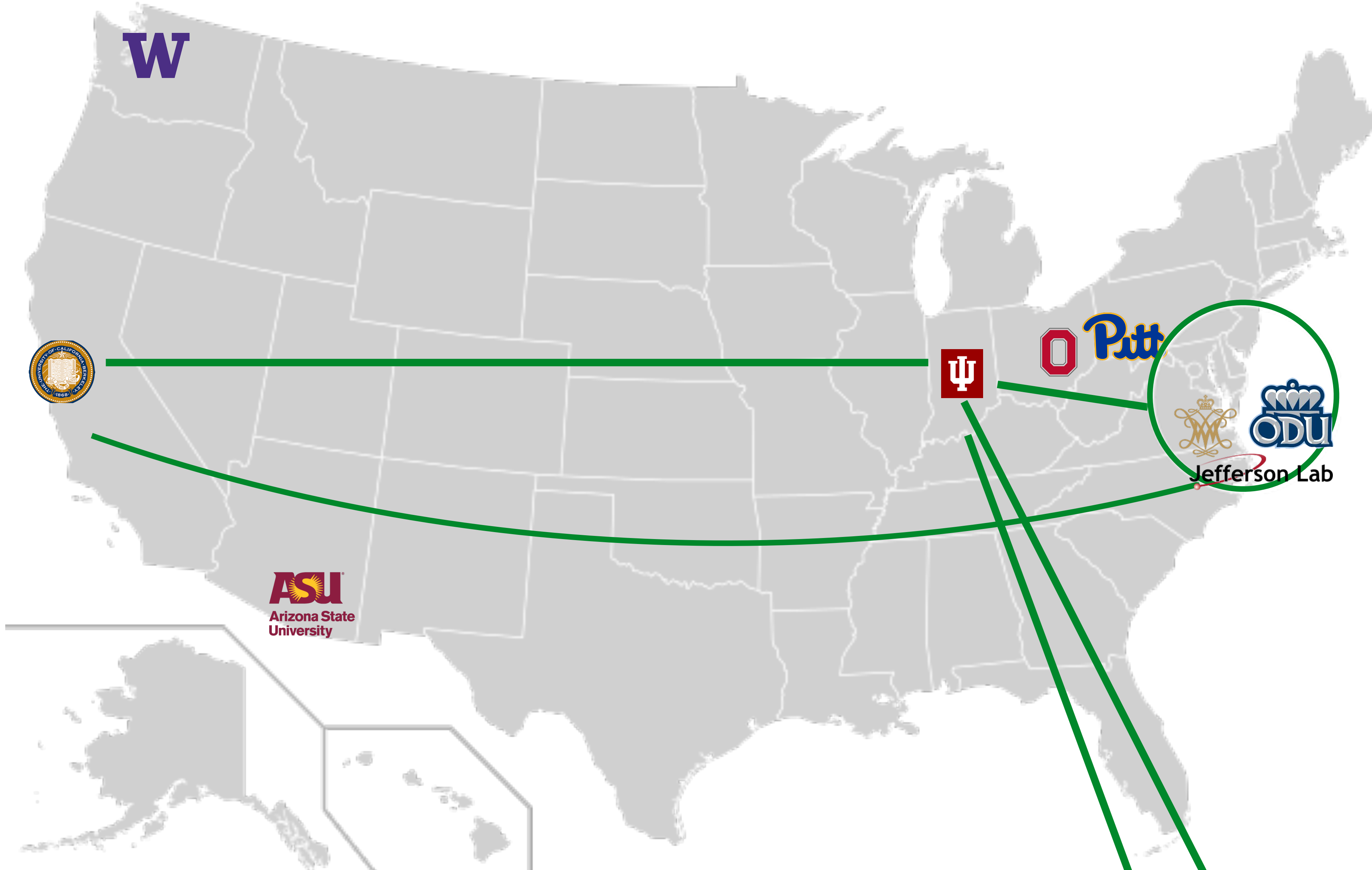
analysis phenomenology lattice


W
Pitt
GW
ODU
Jefferson Lab
ASU
Arizona State University


UNI GRAZ
UNED



lattice three-body formalism





# amplitude model-building



# phenomenology

# ExoHad Collaboration Bylaws

Administration

Last updated on Jan 15, 2024

## Mission Statement

The mission of the ExoHad Collaboration is to assist in the discovery and understanding of novel forms of strongly interacting matter by leveraging interdisciplinary state-of-the-art technical expertise in lattice field theory, phenomenological modeling, and amplitude analysis as constrained by Quantum Chromodynamics.

## Governance

The voting body consists of full members of the ExoHad Collaboration (referred to as 'the TC' in the following).

Full members are the co-PI's as listed in the DOE Topical Collaboration proposal and all new members as agreed by the voting body.

TC members include all full members and all junior members of the collaboration.

Each year the voting body will elect two spokespersons from within the voting body. This vote will take place no later than June 30.

The spokespersons assume responsibility for the smooth operation of the TC including, but not limited to, managing the budget, ensuring hires are timely and are fairly conducted, resolving conflict of interest and code of conduct problems, maintaining the collaboration website, and organizing TC meetings.

New TC members must be invited by a full member and approved by a majority of the voting body.

Quorum for all votes will be set at 2/3 of the voting body membership. Absentee voting is permitted. Voting will be anonymous.

# ExoHad Code of Conduct and Statement of Values

Administration

Last updated on Nov 17, 2022

This Code of Conduct outlines the basic standards of behavior to which we, as members of ExoHad, must adhere. This code was developed democratically and collaboratively, and expresses our collective vision of ethical research. While the code of conduct aims to be general, it cannot be prescriptive for all circumstances. Thus it falls upon each ExoHad member to, in any given situation, act in good faith and with good intentions. Our core beliefs are summarized in the following themes:

## Diversity

We value an open, diverse, and inclusive working environment, which fosters respect and inclusion of all parties. We believe that the highest quality of scientific work is only possible if people are empowered to express themselves openly and honestly, and are treated with respect. Thus, we abstain from all forms of discriminatory behavior including (but not limited to) on the basis of age, religion, political affiliation, nationality, culture, ethnicity, race, sexual orientation, gender identity, gender expression, ability status, family situation, or any other characteristic of personal identity. As part of our commitment to diversity, we encourage participation in outreach programs.

## Behavior

Disruptive or harassing behavior of any kind will not be tolerated. Harassment includes, but is not limited to, inappropriate or intimidating behavior and language, unwelcome jokes or comments, unwanted touching or attention, offensive images, photography without permission, bullying, stereotyping, put-downs, and stalking.

## Integrity and Rigor

Trust between collaborators is integral for open and honest communication. In the pursuit of high-

# Milestones

## 2023

Milestone **3** (Lattice):

Extension of finite-volume three-body formalism to scattering of particles with spin

Quartile: Q2, Status: **Completed**, Responsible: Stephen Sharpe

Papers: JHEP **07** (2023), 226

News: Extension of finite-volume three-body formalism to scattering of particles with spin

Milestone **1** (AmpAn):

Mass-independent partial-wave analysis. Determine the existence of ambiguities in mass independent PWA of two-pseudoscalar meson photoproduction

Quartile: Q3, Status: **Completed**, Responsible: Adam Szczepaniak

Papers: Phys. Rev. D **108** (2023), 076001

News: No ambiguities in the partial wave analysis for hybrids

Milestone **4** (Lattice):

First dispersive extractions of the $\sigma/f_0(500)$ from lattice QCD at various light-quark masses

Quartile: Q3, Status: **Completed**, Responsible: Arkaitz Rodas Bilbao

Papers: Phys. Rev. D **109** (2024), 034513; Phys. Rev. D **108** (2023), 034513

News: Dispersion relations and Lattice QCD pinpoint the $\sigma$ meson

Milestone **6** (Pheno):

Calculation of decays of $T_{cc}^{+}(3875)$ in XEFT at LO, and determining implications of the systematic treatment of the nearby coupled 2-body channel for lighter exotic hadrons

Quartile: Q3, Status: **Partially completed**, Responsible: Eric Braaten

Papers: arXiv:2403.12868

Milestone **8** (Pheno):

Take advantage of the GlueX measurements on photoproduction of vector mesons to perform quantitative analysis of their implications for fundamental properties such as the proton mass radius

Quartile: Q4, Status: **Partially completed**, Responsible: Jinfeng Liao

Papers: Phys. Rev. D **108** (2023), 054018

News: Revisiting $J/\psi$ photoproduction at threshold

## 2024

Milestone **13** (Lattice):

Extension of finite-volume three-body formalism to more general cases of multiple coupled systems

Quartile: Q2, Status: **Completed**, Responsible: Stephen Sharpe

Papers: arXiv:2403.20064

News: Three particles with coupled channels

# 2023

## milestone 2

Formulate and apply mass-dependent amplitude analysis to describe Δ++ production and explain the momentum transfer behavior of the beam spin asymmetry (Szczepaniak IU, Y1Q3)

***Delayed to align the theory development with GlueX analysis.***

## milestone 5

Lattice QCD calculation of the 3π scattering amplitude when ππ can form the ρ resonance. (Briceño UCB, Y1Q4).

***In progress. A key outstanding problem related to the the amplitude analysis for the rho-pi system was resolved in: "Partial-wave projection of the one-particle exchange in three-body scattering amplitudes", Andrew W. Jackura & Raúl A. Briceño, e-Print: 2312.00625 [hep-ph], PRD (accepted).***

## milestone 7

Computation of decays of X(3872) at NLO in XEFT, which requires solving the problem of large NLO corrections, and determine implications of the systematic treatment of the coupled 3-body channel for lighter exotic hadrons. (E. Braaten OSU, Y1Q3).

***Replaced with BO analysis of heavy quark exotics.***

# 2023

## Related work

***"Light hybrid meson mixing and phenomenology", E.S. Swanson, Phys.Rev. D 107 (2023) 7, 074028.***

## Related work

***"Heavy-quark spin symmetry breaking in the Born-Oppenheimer approximation", R. Bruschini, JHEP 08 (2023) 219.***

# 2024

## milestone 9

Formulate and apply mass-dependent PWA parametrizations (K-matrix, N/D, dispersion relations) for the combined analysis of $\eta\pi$, $\eta'\pi$ and three-particles in the quasi-two-particle approximation. (Rodas JLab, Y2Q2).

***Started, estimated completion in Q3.***

## milestone 10

Calculate exotic Regge trajectories from string and quark models. (Liao IU, Y2Q4).

***In progress.***

## milestone 11

Dispersion relations and FESRs for $\eta\pi$, $\eta'\pi$ with pion beams (relevance to COMPASS data). (Szczepaniak IU, Y2Q4).

***Work is underway, the key hurdle has been overcome.***

## milestone 12

Lattice QCD calculation of $\gamma(\omega, \phi) \to a_0 \to \eta\pi, K\bar{K}$ . (Dudek W&M, Y2Q3).

***Work has started on computing three-point correlation functions.***

## milestone 14

Develop model to determine lowest multiplets of hidden-strange tetraquarks and molecules. (Lebed ASU, Y2Q4).

***Not yet started (waiting for postdoc hire).***

## milestone 15

Compute decays of $T_{cc}{}^{+}$ at NLO in XEFT, which involves the systematic treatment of coupled 2-body and 3-body channels. Consider consequences for possible strange-quark analogue states. (Braaten OSU, Y2Q4).

***Replaced with BO heavy quark objective.***

# 2024

## Related work

***"Why quarkonium hybrid coupling to two S-wave heavy-light mesons is not suppressed", R. Bruschini, Phys.Rev. D 109 (2024) 3, L031501.***

## Related work

***"Model-independent predictions for decays of double-heavy hadrons into pairs of heavy hadrons", E. Braaten & R. Bruschini, e-Print: 2403.12868 [hep-ph]***

# 2025

## milestone 18

Development of formalism to analytically continue three-body integral equations into the complex plane in order to search for resonance pole singularities. (Doring GW, Y3Q4)
***Completed: "Analytic continuation of the relativistic three-particle scattering amplitudes", S.M. Dawid, Md Habib E. Islam, Raúl A. Briceño, Phys.Rev. D 108 (2023) 3, 034016.***

## milestone 23

Identify and compute distinctive decay modes of the exotics to quasi-stable hadronic final states within the dynamical model previously developed. (Swanson U. Pitt., Y3Q4).
***Completed: "A Constituent Model of Light Hybrid Meson Decays", C. Farina, E.S. Swanson, e-Print: 2312.05370 [hep-ph], PRD (to appear).***

# Products

# Publications

Insert a new publication — Statistics

Date | All publications

19 publications 2023-2024

## 2024

C. Farina, E.S. Swanson

A Constituent Model of Light Hybrid Meson Decays

PRD (to appear) (2024); published on April 13, 2024

Cite DOI ArXiv

D. Winney, A. Pilloni, R. J. Perry, Ł. Bibrzycki, C. Fernández-Ramírez, N. Hammoud, V. Mathieu, G. Montaña, A. Rodas, V. Shastry, W. A. Smith, A. P. Szczepaniak

$XYZ$ spectroscopy at electron-hadron facilities III: Semi-inclusive processes with vector exchanges

arXiv:2404.05326; published on April 8, 2024

Cite ArXiv

Z. T. Draper, S. R. Sharpe

Three-particle formalism for multiple channels: the $\eta\pi\pi + K\bar{K}\pi$ system in isosymmetric QCD

arXiv:2403.20064; published on March 29, 2024

Cite ArXiv

E. Braaten, R. Bruschini

Model-independent predictions for decays of double-heavy hadrons into pairs of heavy hadrons

arXiv:2403.12868; published on March 19, 2024

Cite ArXiv

# Talks

Date | Speaker | Talk Type

108 talks 2023-2024
by 29 collab members

## 2024

Roberto Bruschini: Heavy Hybrids in the Born-Oppenheimer Approximation
Invited Talk · 5th Workshop on Future Directions in Spectroscopy Analysis (FDSA2024), Genoa (Italy)
January 22, 2024 — January 24, 2024

Daniel Winney: Charmonium (and beyond) in Photoproduction
Talk · 5th Workshop on Future Directions in Spectroscopy Analysis (FDSA2024), Genoa (Italy)
January 22, 2024 — January 24, 2024
Pdf

Gloria Montaña: Role of pion exchange in photoproduction: from current conservation to reggeization
Talk · 5th Workshop on Future Directions in Spectroscopy Analysis (FDSA2024), Genoa (Italy)
January 22, 2024 — January 24, 2024
Pdf

Gloria Montaña: Amplitude extraction with GANs
Talk · 5th Workshop on Future Directions in Spectroscopy Analysis (FDSA2024), Genoa (Italy)
January 22, 2024 — January 24, 2024
Pdf

Nadine Hammoud: Analyzing Light Resonances in Two-Pion Photoproduction through a Regge Formalism Approach
Talk · 5th Workshop on Future Directions in Spectroscopy Analysis (FDSA2024), Genoa (Italy)
January 22, 2024 — January 24, 2024
Pdf

# Outreach

# Schools/Education

JEFFERSON SCIENCE ASSOCIATES &
HUGS
FELLOWSHIP
FOR GRADUATE STUDENTS
IN DEVELOPING COUNTRIES

César Fernández Ramírez

Gloria Montaña

# Schools/Education


2025: @ Berkeley

# Schools/Education


## JOIN OUR SUMMER 2024 PROGRAM: JUNE 18 - JULY 26

Join the **Remote Experience for Young Engineers and Scientists (REYES)**, a program designed to increase STEM-H literacy, inspire and train the next generation of scientists.

This unique virtual learning experience offers guest lectures in a variety of STEM-H subjects, activities, and mentoring through research-based projects.

Registration is free and open to the public.

### REGISTER TODAY:

physics.berkeley.edu/reyes

Berkeley Physics


## This is a six week course START DATE: JUNE 18, 2024

Python4Physics is a class designed to give students the key tools to write simple code using a programming language called Python. In this class, you will learn some fun concepts in Physics, Math, statistics, and, of course, programming. You will do this by solving problems numerically. You will learn to solve equations, do data analysis, and model various systems. You do not need any background with programming, physics, or calculations. You will need to be familiar with algebra.

**FOR MORE INFORMATION**

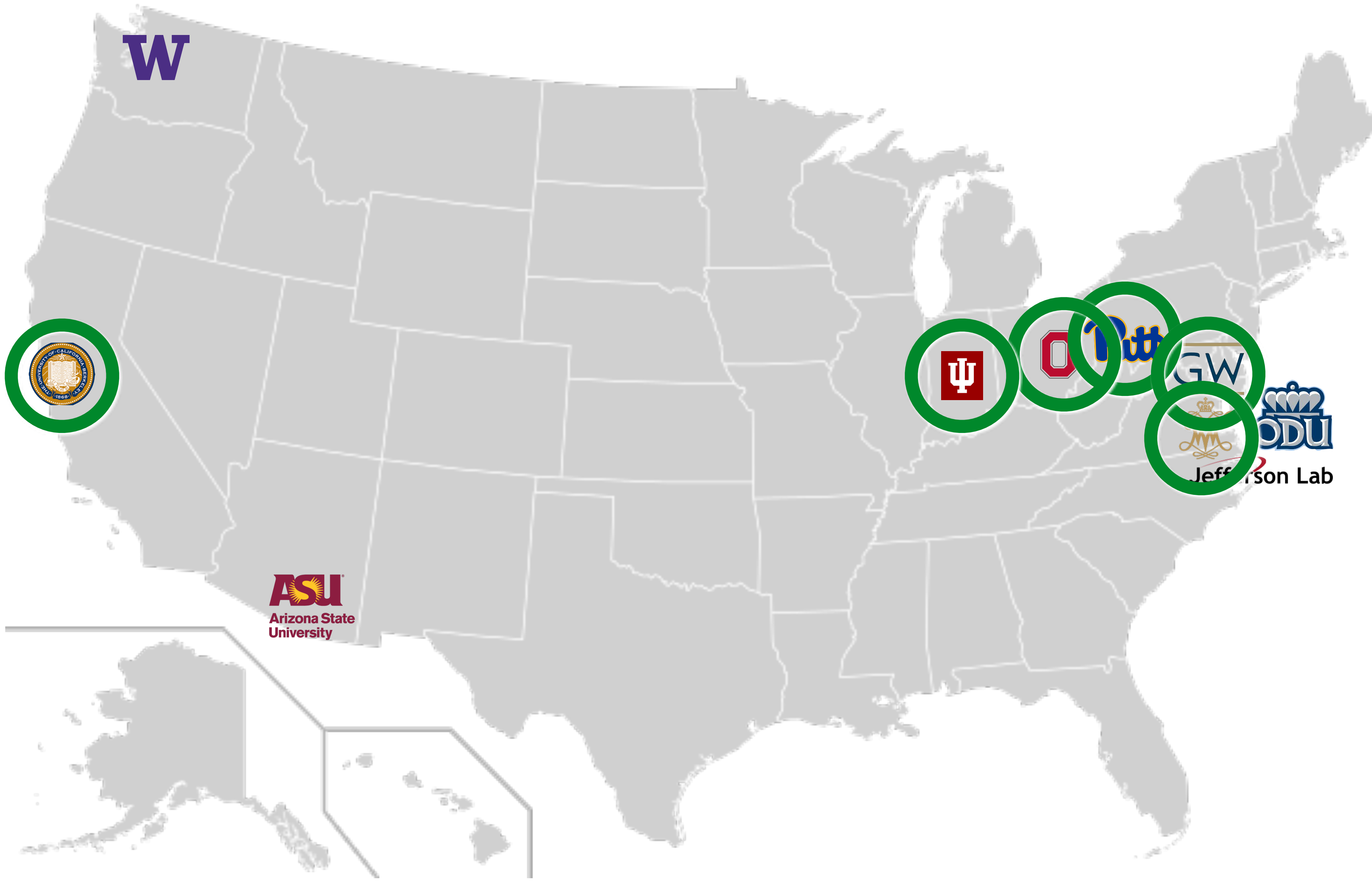
Go to our registration form using the qr code below, or visit: /physics.berkeley.edu/python4physics

Registration is free and open to the public.

### REGISTER TODAY

Berkeley Physics

# ExoHad participation in REYES




# Mentoring

weekly meetings with students

TC meetings every 6 weeks

~$11K in travel funds provided for 5 junior members to date

# Conclusions

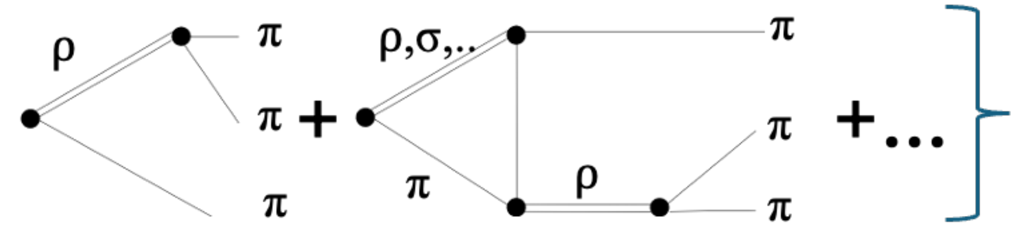
- there is major progress in all areas
- the collaboration is making a difference
- almost all funding goes to junior people
- none of this is possible without funding stability for the senior people

# Backup

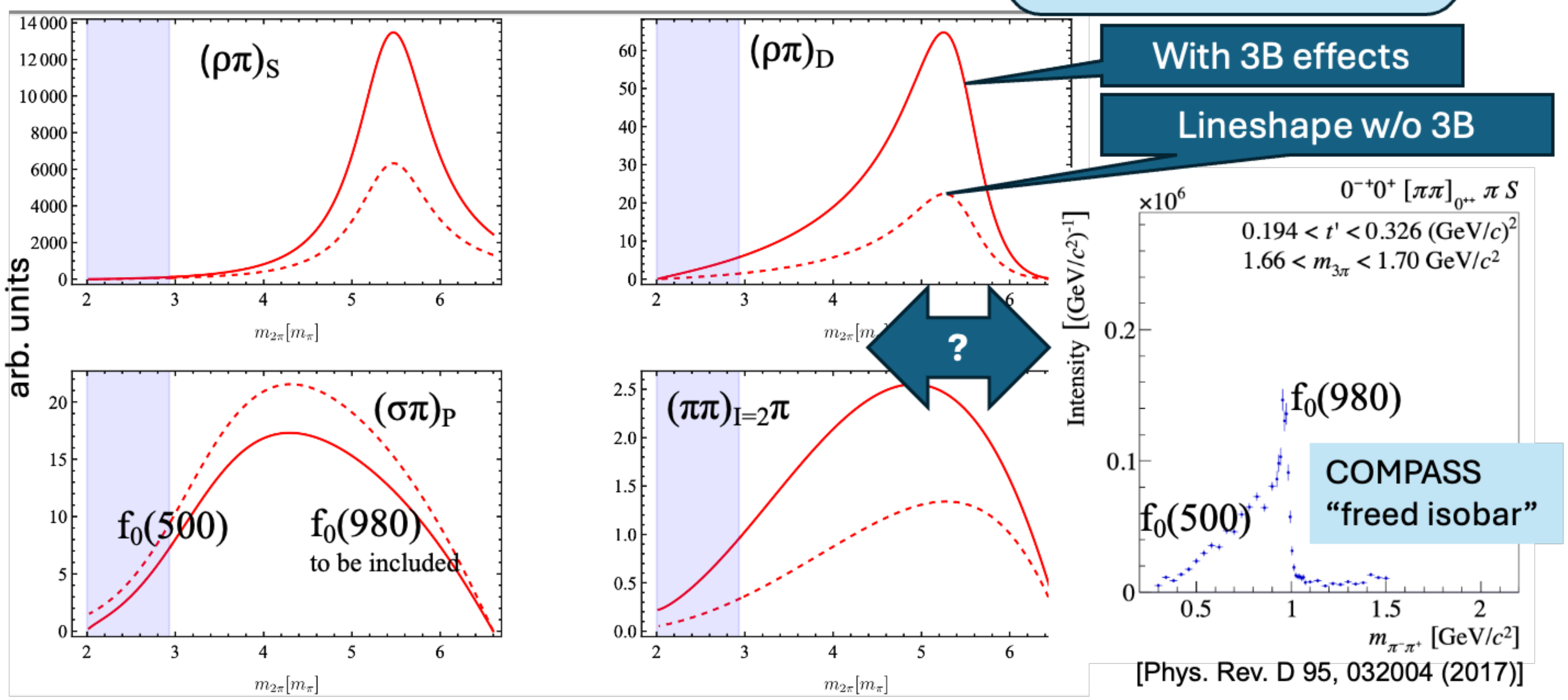
# Rescattering effects for amplitude analysis

- Isobar lineshapes + corrections

Y. Feng, M. Doering,
V. Shastry, A. Szczepaniak




$I^G(J^{PC}) = 1^-(1^{++}) \rightarrow$
$(\rho\pi)_S$, $(\rho\pi)_D$,
$(\sigma\pi)_P$, $(\pi\pi)_{I=2}\pi, \ldots$
$\rightarrow \pi\,\pi\,\pi$




[Phys. Rev. D 95, 032004 (2017)]

## Narrative:

- Determination of resonances with 3-body decays depends on “lineshape” of two-body subsystems that eventually decay to 3 pions, including the “spectator”
- Unitarity provides constraints on coupled-channel 3-body rescattering that add to traditionally used “isobars”, modifying the lineshape.
- Preliminary/first numerical results on 4-channel rescattering for the example of the $a_1$(1260) quantum numbers:
    - Invariant mass of different isobars on x-axis: rho(700) that has two possibilities (S- and D-wave), f0(500) ”sigma”, and repulsive pipi in isospin I=2 which is also P-wave. Inclusion of f0(980) still missing (compare COMPASS lineshape & lower left picture in the 4-picture array).
    - dashed lines: naive isobar, like in left ”Feynman” diagram
    - solid lines: including coupled-channel rescattering (corrections like right drawing plus higher-order rescattering)
    - → Lineshapes are modified beyond arbitrary multiplicative factor
- Lower right: COMPASS experiment takes such effects into account by phenomenological “freed isobar” .
- <u>Questions to be addressed</u>: How does coupled-channel rescattering compare to “freed isobars” (left-right arrow with question mark on the slide)

**Background info:**

- Two-body subsystems are parametrized via Inverse Amplitude Method and fit respective two-body phase shifts
- 3B scattering equation solved on complex momenta and then continued to real momenta using the Heatherington-Schick method (non-trivial in the blue shaded areas), if anyone asks.

# Eichmann

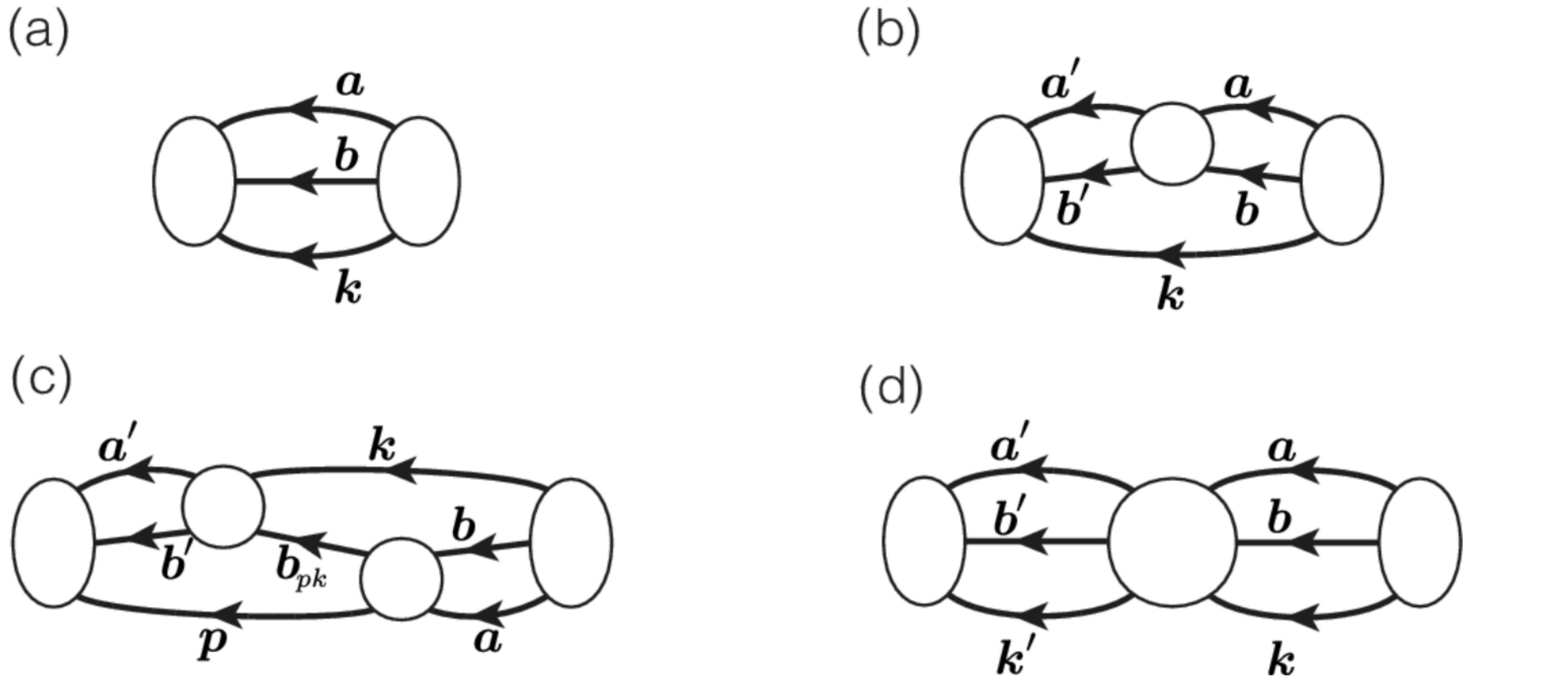
- **Tetraquarks:** in a recent paper we calculated the spectrum of ground and excited four-quark states in the charm and bottom region using functional methods. We find that that their internal structure differs depending on the quantum numbers; states with CP = 1 are dominated by heavy-light meson contributions, whereas for axialvector mesons the picture is more complicated and depends on the flavor content. A follow-up work for open-flavor states is currently in preparation.

  J. Hoffer, G. Eichmann, C. S. Fischer, "Hidden-flavor four-quark states in the charm and bottom region", Phys. Rev. D (2024), in print. arXiv:2402.12830 [hep-ph]

- **Pentaquarks:** We are working on the 5-body equation for heavy-light pentaquarks in order to investigate the spectrum and structure of the 'LHCb pentaquarks'. To this end, my PhD student Raul Torres solved the whole cascade of 2-, 3-, 4- and 5-body equations in a scalar model, a paper is currently in preparation.

- **Hexaquarks:** Together with my master (and hopefully future PhD) student André Nunes, we constructed the two-body version of the six-body equation, in analogy to the quark-diquark model for baryons, and applied it to the deuteron. The results so far are promising and may give us a glimpse in how quark and gluon effects cancel out to leave pion and sigma exchange as the predominant binding of the deuteron. We are currently performing further checks, a paper will follow.

- Tetraquarks: Christian Fischer, Joshua Hoffer
- Pentaquarks: Raul Torres, Teresa Pena
- Hexaquarks: André Nunes, Teresa Pena, Ana Arriaga




The extension to include spin in the three-particle formalism was carried out in the context of the three-neutron system in a paper by ExoHad members Zack Draper (UW graduate student) and Steve Sharpe (UW, co-PI) in collaboration with Max Hansen (Edinburgh) and Fernando Romero-Lopez (MIT). The inclusion of spin is more complicated for three-particle systems than for two-particles, because of the need to consider several reference frames: the overall center-of-mass frame (CMF), and the three choices of pair CMFs. This leads to the presence of Wigner rotations in the formalism, and thus nontrivial spin-dependence. The inclusion of spin also complicates the form of the three-particle K-matrix that enters in the formalism. Although the explicit results are for three identical spin-1/2 particles, the methods are straightforward to generalize to other systems, including higher spins and nonidentical particles.

Papers: JHEP **07** (2023), 226

# Sharpe

The extension of the three-particles formalism to multiple three-particle channels has been carried out by ExoHad members Zack Draper (UW graduate student) and Steve Sharpe (UW, co-PI), in a paper submitted to the arXiv. This is done in the context of the ,, ,, , and $K\bar{K}\pi$ system in isosymmetric QCD, where, if one enforces positive G parity, as well as conservation of $J^P$, there is no mixing with the $2\pi$ or $3\pi$ systems. This two-channel system is suitable for studying the $b_1(1235)$ and $\eta(1295)$ resonances, as long as one ignores coupling to channels with four or more particles.

Papers: arXiv:2403.20064

For the 2024 milestone, this is the status:

Extension of finite-volume three-body formalism to more general cases of multiple coupled systems ({\it Sharpe} UW, Y2Q2).

The extension of the three-particles formalism to multiple three-particle channels has been carried out by ExoHad members Zack Draper (UW graduate student) and Steve Sharpe
PI), in a paper submitted to the arXiv [arXiv:2403.20064]. This is done in the context of the $\pi\pi\eta$ and $K \bar K \pi$ system in isosymmetric QCD, where, if one enforces posit
parity, as well as conservation of $J^P$, there is no mixing with the $2\pi$ or $3\pi$ systems. This two-channel system is suitable for studying the $b_1(1235)$ and $\eta(1295)$ res
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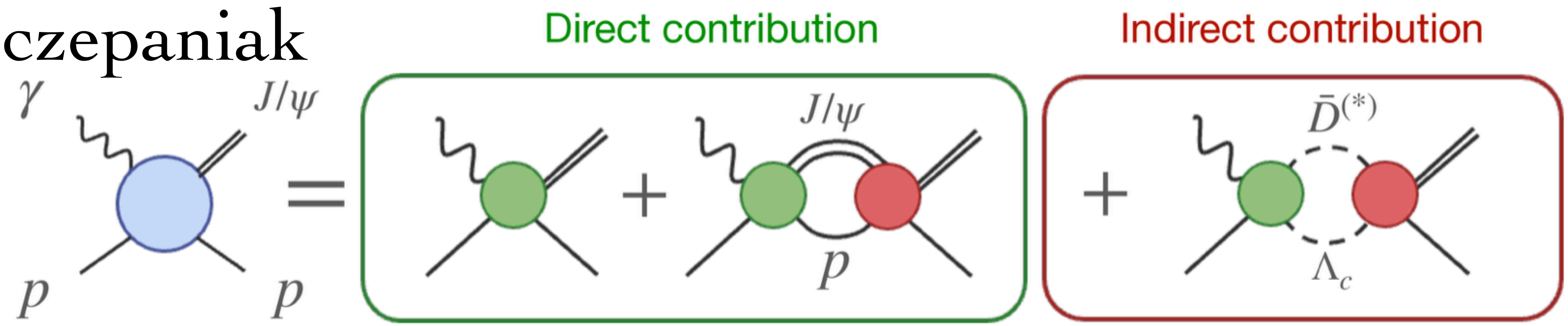
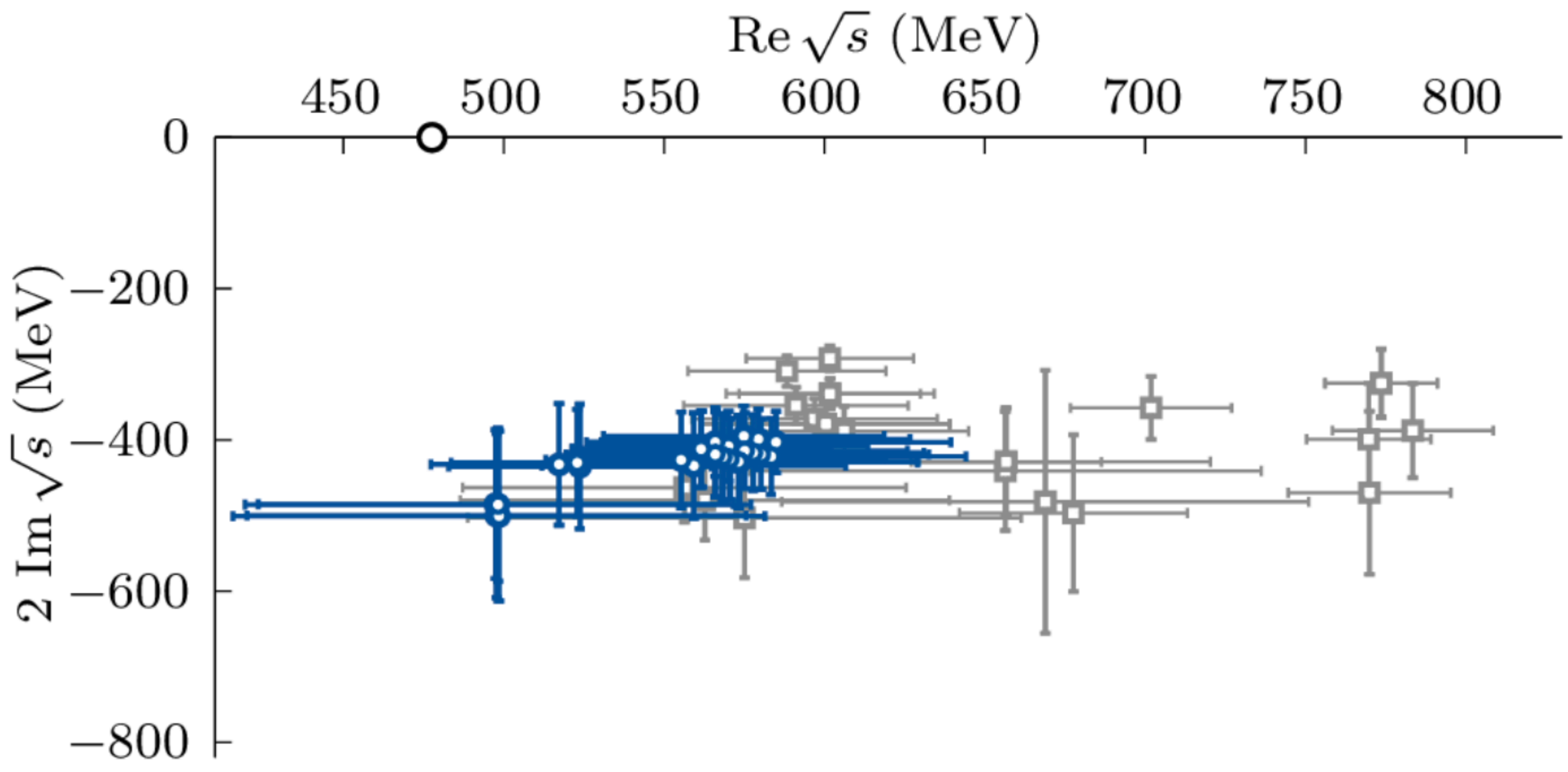
# Szczepaniak



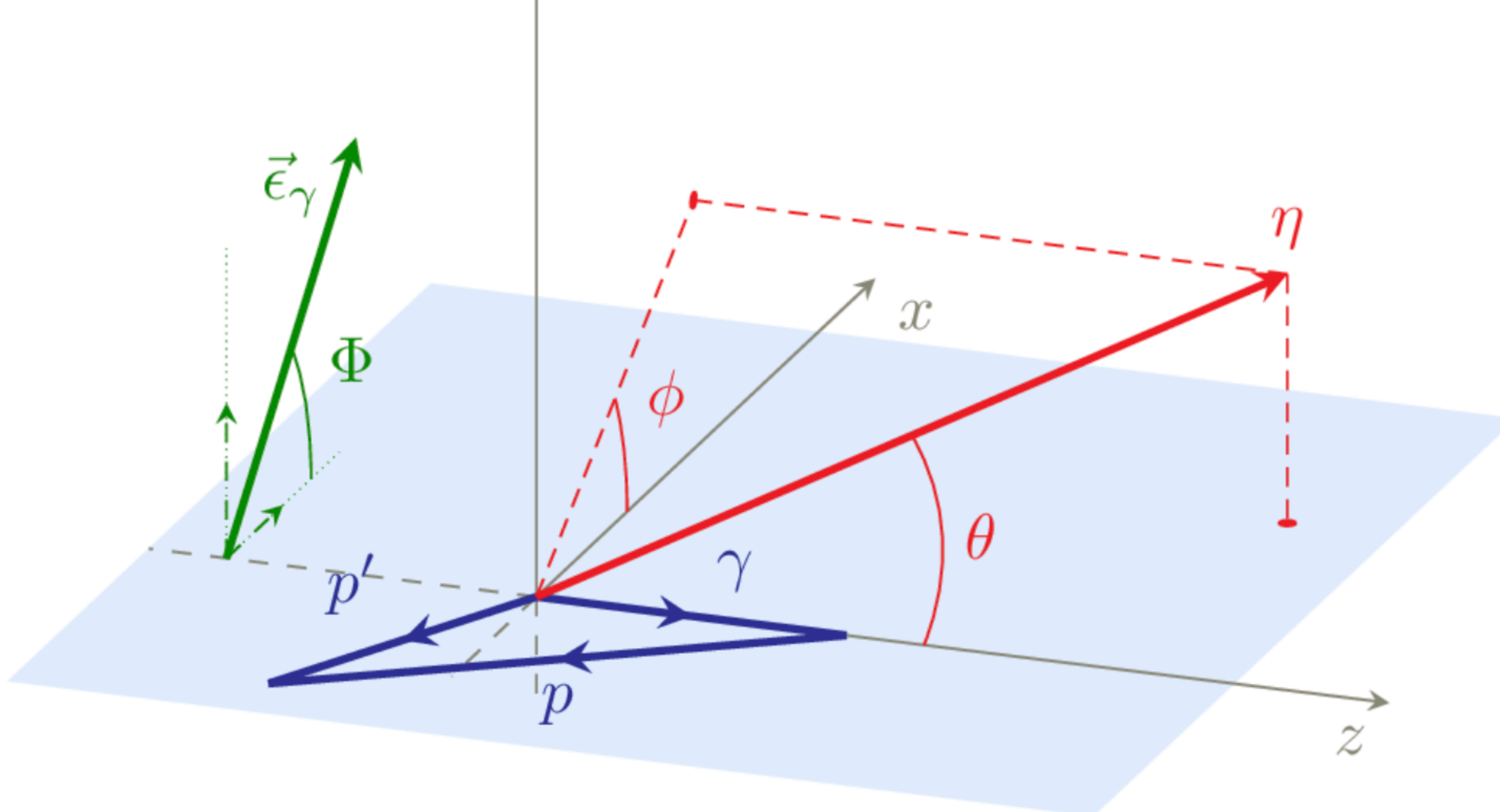

The study of $J/\psi$ photoproduction at low energies has consequences for the understanding of multiple aspects of nonperturbative QCD, ranging from mechanical properties of the proton, to the binding inside nuclei, and the existence of hidden-charm pentaquarks. A work by the JPAC collaboration, led by Daniel Winney (SCNU), Cesar Fernandez-Ramirez (UNED & UNAM), and Alessandro Pilloni (Messina), Adam Szczepaniak (Indiana U., PI), and Jinfeng Liao (Indiana U., co-PI), together with Astrid Hiller Blin (Tubingen), Miguel Albaladejo (IFIC Valencia), Lukasz Bibrzycki (AGH Krakow), N. Hammoud (INP Krakow graduate student),Vincent Mathieu (Barcelona U., co-PI), Gloria Montana (JLab), Robert Perry (Barcelona), Vanamali Shastry (Indiana), Wyatt Smith (IU graduate student), reanalyzes the latest photoproduction cross sections from GlueX and the $007-J/\psi$ experiments at Jefferson Lab. The results suggest a nonnegligible contribution from open charm intermediate states and an incompatibility with Vector Meson Dominance, which might affect the extraction of the gravitational form factor of the proton and needs to be properly understood. A wide array of physics possibilities that are still compatible with present data need to be disentangled.

Papers: Phys. Rev. D **108** (2023), 054018




Lattice QCD is the model-independent, theoretical approach to study low-energy strong interactions. We can study unstable particles, known as resonances, using modeled reaction amplitudes describing lattice QCD spectra. These amplitudes satisfy only a subset of the mathematical requirements, unitarity, but fail to implement crossing symmetry and analyticity. This is a problem when extrapolating amplitudes far from the data region, e.g. in the case of resonances like the $\sigma$, leading to large systematic uncertainties in the pole position. In these works carried out by Arkaitz Rodas (ODU, co-PI), Jo Dudek (JLab/W&M, co-PI), and Robert Edwards (JLab, co-PI), we show how dispersion relations implement the additional constraints to reduce the allowed combination of parameterizations describing previously lattice-determined $\pi\pi$ partial waves. As a result, the $\sigma$ pole position is determined with minimal systematic uncertainty. Combining these with previous results, we provide a determination of the $\sigma$ particle's fundamental parameters for four values of the pion mass.

Papers: Phys. Rev. D **109** (2024), 034513; Phys. Rev. D **108** (2023), 034513




The extraction of partial waves from experimental cross sections can be plagued by mathematical ambiguities, that is by the fact that different sets of partial waves can lead to the very same physical observables. This fact was originally studied in the spinless case, and it is known as Barrelet zeroes. When particles carry spin, the presence of additional polarization observables can help resolving those ambiguities. While there is no general solution to this problem, it is important to focus on the practical cases that are useful for the detection of hybrids at GlueX. A work by the JPAC collaboration, led by Wyatt Smith (IU graduate student), Vincent Mathieu (Barcelona U.), and Derek Glazier (Glasgow U.), studied the ambiguities in the partial wave analysis of double scalar meson photoproduction (say $\eta\pi$) with a linearly polarized beam. A new formalism that makes special use of beam asymmetries shows that, for most reasonable wave sets of a single reflectivity, the information available is sufficiently constraining, so that we different partial wave sets can always be disambiguated, thus ruling out the possibility of discrete ambiguities in this type of analysis.

Papers: Phys. Rev. D **108** (2023), 076001

Postdoc Roberto Bruschini and I are closing in on a definitive solution to the problem of exotic heavy mesons by explo
the diabatic formulation of the Born-Oppenheimer approximation for QCD.
I have put my efforts towards my EXOHAD milestones on hold, because the solution to this problem will have a much larger impact on the overall goals of the ExoHad collaboration.

Model-independent predictions for decays of double-heavy hadrons into pairs of heavy hadrons

#1

- E. Braaten, R. Bruschini (Mar 19, 2024)
    - e-Print: 2403.12868 [hep-ph]

Why quarkonium hybrid coupling to two
S
-wave heavy-light mesons is not suppressed

#3

- R. Bruschini(Ohio State U.) (Jun 29, 2023)
    - Published in: *Phys.Rev.D* 109 (2024) 3, L031501 • e-Print: 2306.17120 [hep-ph]

Heavy-quark spin symmetry breaking in the Born-Oppenheimer approximation

#4

- R. Bruschini(Ohio State U.) (Mar 30, 2023)
    - Published in: *JHEP* 08 (2023) 219 • e-Print: 2303.17533 [hep-ph]